Resilience and sustainability in the management of landslides

Phillip N. Flentje
University of Wollongong, pflentje@uow.edu.au

Robin N. Chowdhury
University of Wollongong, robin@uow.edu.au

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Abstract

There are many regions worldwide which are susceptible to landslides, which cause loss of life and adverse impacts to infrastructure, environment and communities. Landslides are often triggered by exceptional rainfall and large-magnitude earthquakes. A range of strategies and methods have been developed to mitigate the occurrence of landslides and to reduce their impact, including risk to human safety. The adopted approaches and systems must be sustainable and resilient in relation to the communities that are at risk. This paper refers to an Australian regional case study of urban landslide management in the Wollongong region, New South Wales. The research carried out by the authors over two decades at the University of Wollongong has enhanced the resilience and sustainability of landslide management in the region. Reference is also made to Hong Kong as a case study of urban regional landslide practice, with particular reference to the upgrading of man-made slopes.

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resilience, management, landslides, sustainability

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Flentje and Chowdhury

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Phil Flentje PhD
Senior Research Fellow, Faculty of Engineering and Information Sciences, University of Wollongong, Wollongong, Australia (corresponding author: pflentje@uow.edu.au)

Robin Chowdhury PhD
Emeritus Professor, Faculty of Engineering and Information Sciences, University of Wollongong, Wollongong, Australia

There are many regions worldwide which are susceptible to landslides, which cause loss of life and adverse impacts to infrastructure, environment and communities. Landslides are often triggered by exceptional rainfall and large-magnitude earthquakes. A range of strategies and methods have been developed to mitigate the occurrence of landslides and to reduce their impact, including risk to human safety. The adopted approaches and systems must be sustainable and resilient in relation to the communities that are at risk. This paper refers to an Australian regional case study of urban landslide management in the Wollongong region, New South Wales. The research carried out by the authors over two decades at the University of Wollongong has enhanced the resilience and sustainability of landslide management in the region. Reference is also made to Hong Kong as a case study of urban regional landslide practice, with particular reference to the upgrading of man-made slopes.

1. Introduction

1.1 Causes and impacts of slope instability

Understanding the factors which control slope stability is essential for identifying the causes of the potential failure of a slope and the development process of a landslide. Assessing landslide susceptibility and hazard in both spatial and temporal dimensions requires knowledge of the causes, as well as the important regional and local influencing factors. Due to increasing population, deforestation, urbanisation and poorly controlled development, landslide hazard and the vulnerability of assets and communities have been increasing over many decades. Consequently, the risk of landsliding has also increased significantly in many regions of the world.

The death toll due to landslides on the global scale is large and, according to recent research by Petley (2012), has generally been underestimated. His research on non-seismic landslides found that 2620 fatal landslides had been recorded over the period of 2004–2010, resulting in 32 322 deaths. There is considerable geographical variability in the occurrence of landslides due to differences in geological environment, population density, climate and vulnerability. Landslide-related fatalities are particularly high in mountainous countries with fragile geological environments.

The mentioned number excludes the enormous death toll from landslide disasters triggered by earthquakes of large magnitude. Examples are the 26 500 lives lost due to landslides following the northern Pakistan (magnitude 7·6) earthquake of 8 October 2005 (Petley *et al*., 2006) and 20 000 lives lost due to landslides caused by the Wenchuan (magnitude 7·9) earthquake of 12 May 2008 in south-west China (Chigira *et al*., 2010).

1.2 Resilience and sustainability in the context of landslide management

Geohazard reduction and risk mitigation must be guided by sound technical knowledge in geotechnical engineering, geology and other disciplines. In addition to developmental and economic aspects, there often are social, environmental and political issues which cannot be ignored in developing landslide management strategies (refer to, for example, Anderson and Holcombe (2013)). The scope and application of landslide risk management has to be tailored to the availability of economic resources.

From a geotechnical perspective, the reliability of slopes relative to that of structures or facilities located on them is important. For instance, after an earthquake disaster in a mountainous region, structures must be built or retrofitted to the latest codes and standards. If such structures are located on or near sloping ground which is susceptible to landsliding, then the appropriate landslide risk management practices must be applied. Ideally, the reliability of the slopes after remediation must be the same or higher than the reliability of the new or retrofitted structures.

The resilience of management processes should be considered for currently stable slopes as well as for pre-existing landslides. In both cases, the aim should be to reduce hazard in ways that are cost effective as well as robust for the medium to long term. The goal should be to reduce the probability of the occurrence of landslide events as well as to mitigate the severity of disruption and other adverse consequences. Global institutions concerned with disaster management often refer to resilience and sustainability (UNISDR, 2012; WEF, 2015), but there is a lack of guidance about the basic steps required for landslide management.

1.3 Gap between geotechnical research and practice

Academics and researchers may not fully appreciate the realities of the geotechnical profession. On the other hand, geotechnical engineers often are not up to date with the recent research. There may be poor focus on implementing the knowledge and adopting the latest research methods for practical use.

While the gap between knowledge and practice can be observed in all countries, it is particularly large and persistent in developing societies with low economic and technical resources. A recent case in point is the disastrous Nepal earthquake of 2015, which triggered many landslides (Geer, 2015). Hundreds of millions of dollars have been pledged in external aid, but there has been very little landslide remediation, although more than a year has passed (Kumar and Sindhupalchok, 2016).

2. Aim and scope of this paper

The main aim of this paper is to highlight the management of landslides, with particular reference to resilience and sustainability. To achieve this aim, it is important to summarise the available methods for both site-specific and regional assessment of landslide susceptibility and hazard.

Two urban regions, located in different continents and with quite different geological, geotechnical and topographic features, are included for brief consideration in this paper. The first urban region considered in this paper is Wollongong in New South Wales (NSW), Australia. This region has been the focus of significant research effort and industry collaboration by the authors as part of the Landslide Research Team (LRT) at the University of Wollongong (UOW). The city of Wollongong is located 70 km south of Sydney, on the east coast of NSW, Australia. The population of the Wollongong region is about 200 000 people. The coastal plain is triangular and is bounded to the north, west and south by the erosional Illawarra escarpment, ranging in height from 300 to 500 m, as illustrated in Figure 1, while the head scarp of a typical slide–flow-category landslide is shown in Figure 2.

The second urban region considered briefly in this paper is Hong Kong, where the work done in the field of slope stability and urban landslide management has received considerable international attention. Engineers and researchers have been active in improving the state of the art of slope engineering and landslide hazard reduction. The information presented in this paper on landslide management and research in Hong Kong is entirely based on published articles and on knowledge gained through study and interactions with other researchers and engineers.

In both regions, landslides triggered by high rainfall, impacting infrastructure and housing, have been managed over several

Figure 1. Location of Wollongong study area and oblique photograph looking south along the Illawarra escarpment

Figure 2. Slide–flow head scarp near Mount Kembla village triggered by rainfall on 17 August 1998

decades. Moreover, research effort has steadily increased and better methods of hazard assessment and risk management have evolved in both urban areas. Thus, it is of great interest to have an overview of landslide management in both locations in this paper. Owing to the direct involvement of the authors, the Wollongong practice and research receives greater attention in this paper.

3. Methods for assessing slopes and landslides

3.1 Site-specific analyses, regional assessments and the observational approach

The methods of assessing slopes and landslides can be considered in two main categories: site specific and regional. Site-specific approaches require information about geoengineering parameters, in addition to slope geometry and potential failure mechanisms. Deterministic methods for slide-category landslides include limit equilibrium methods in which the main output is the factor of safety and stress-deformation methods from which distributions of strains, deformations and failed zones within the analysed slope are obtained. Such methods may be complemented by probabilistic methods which take uncertainties into consideration in a systematic manner. Challenges posed by uncertainties and the need for reliable approaches for assessment of urban slope stability have been discussed previously by Chowdhury *et al.* (2010, 2012). Approaches other than limit equilibrium and stress deformation are often required to model landslide types other than slides, such as debris flows and rockfalls.

Regional approaches are generally based on susceptibility and hazard assessment and require spatial information about geology, topography, elevations, drainage and other aspects. Such methods range from qualitative to semi-quantitative, and the results are essential for carrying out risk assessment. Risk assessment methods involve consideration of both ‘hazard’ (likelihood/probability) of landsliding and the potential ‘consequences’ to elements at risk, which must be carefully identified. The most important aspects to consider are adverse impacts to human safety and to economic assets. In addition to the ‘value’ of each element at risk, its degree of ‘exposure’ must be assessed as well as its ‘vulnerability’.

A basic checklist of all methods of hazard and risk assessment, including observational approaches, is shown in Figure 3. Owing to space limitations, only the regional susceptibility and hazard assessment method is considered in some detail with particular reference to the research carried out for the Wollongong region (Sections 3.2 and 3.3). The observational approach, based on instrumentation and monitoring of slopes, is considered only briefly (Section 3.4).

3.2 Assessing landslide susceptibility and hazard

Landslide susceptibility studies are often carried out for an area or region, rather than at individual locations, and a variety of methods can be used. Such approaches facilitate planning for mitigation of geohazards, in particular in urban areas (Gibson and Chowdhury, 2009). Strategies and methods range from entirely qualitative to semi-quantitative and, in the best alternatives, to sophisticated knowledge-based modelling.

Entirely qualitative methods may be based on visual site inspection of different areas and knowledge of geology, topography and other local factors. Susceptibility or hazard is rated using categories such as very high, high, moderate and low. The results for a region are often presented in the form of zoning maps.

Quantitative or semi-quantitative methods are carried out within the framework of a geographical information system (GIS) by combining data sets relating to topography, geology, drainage, existing landslides and other factors. A variety of approaches and methods have been developed and applied to many regional case studies around the world. The best among these methods are fairly sophisticated and make good use of the detailed knowledge concerning existing landslides. Again, the results for a region are presented in the form of maps indicating zones of susceptibility rated in different categories of susceptibility, as mentioned earlier. The elements of a regional assessment process are summarised in Figure 4.

3.3 Assessing risk based on a hazard–consequence approach

The basic concept for assessing risk is to consider it as an intersection of hazard and consequences. Noting that the consequences depend on the value, exposure and vulnerability of elements at risk, one may generically write the following form of equation for a typical element

$$\begin{aligned}\text{Risk} &= \text{hazard} \times \text{consequences}\\ &= \text{hazard} \times \text{vulnerability} \times \text{exposure} \times \text{value}\end{aligned} \tag{1}$$

At the fully qualitative level, both hazard and consequences may be rated in several categories ranging from very high to low, as mentioned in the previous paragraphs. Then, a matrix of hazard

Site-specific methods	Risk assessment methods
• Limit equilibrium methods/models for slide-type landslides (factors of safety)	• Qualitative risk assessment: defines different grades of risk (to assets or to human safety) based on hazard and consequences
• Stress-deformation methods for a continuum or discontinuum (strains, displacements, failed zones)	• Quantitative risk assessment, intersection of hazard, vulnerability and exposure (quantified risk to assets or human safety)
• Probabilistic methods (reliability index, probability of failure, system reliability)	Observational approaches
• Modelling of flows, in particular long runout debris flows (reach and velocities of runout)	• Monitoring of displacements, surface and subsurface, pore water pressures, rainfall
• Modelling of rockfalls (modes of failure and spatial distribution of debris)	• Periodic monitoring of the variables at each instrumented site
Regional susceptibility and hazard assessment methods	• Continuous monitoring of the variables at each instrumented site (online, real-time link to nominated stakeholders)
• Qualitative methods (grades of susceptibility/hazard at specific locations or in the form of maps showing different zones)	Concepts
• Quantitative or semi-quantitative methods: accurate maps for each main category of landslides (slides, debris flows and rockfalls)	Critical slip surfaces, residual shear strength, progressive failure, fluctuating pore pressures, landslide inventories

Figure 3. Site-specific and regional landslide assessment methods

and consequences is prepared so that risk can also be rated in categories ranging from very high to low. To obtain the total risk over all the elements at risk, the assessments for individual elements are combined in a suitable way.

At the quantitative or semi-quantitative level, the hazard of landsliding may be assessed as a probability (range 0–1). As regards the consequences, both the exposure of an element at risk and its vulnerability may be quantified as proportions or probabilities (range 0–1).

Where human safety is at risk, the exposure and vulnerability of individuals and groups should also be considered. In quantitative risk assessment (QRA), the risk to human life is expressed as an annual probability. For instance, the annual risk of a fatality of 1 in 10 000 (10^{-4}) may be regarded as acceptable. However, a much higher annual risk level of 1 in 100 (10^{-2}) is often considered to be unacceptable.

Criteria defining such boundaries between acceptable and unacceptable risks are an important part of developing risk

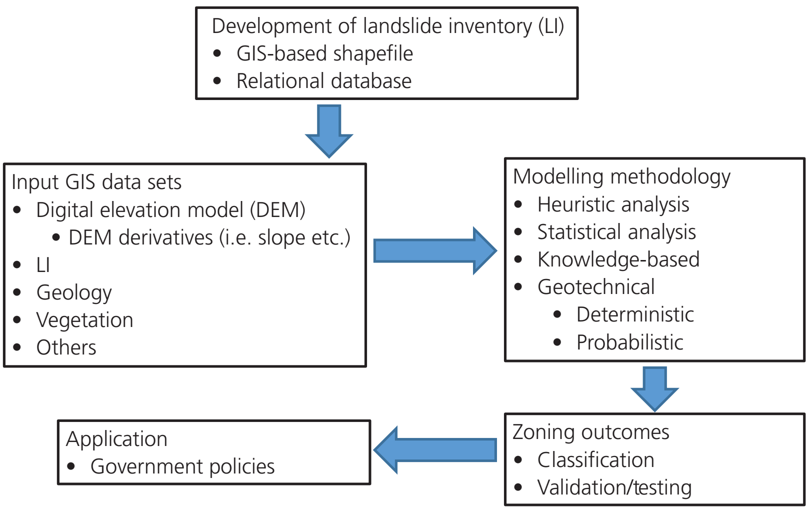

Figure 4. Regional landslide management process

management strategies. These are usually presented as *f–N* curves relating the frequency *f* to the number of fatalities *N*, as reported by the Australian Geomechanics Society (AGS, 2007). The symbol *f* actually represents an acceptable risk level or range. The term 'frequency' is used because *f–N* curves were originally developed in relation to risk assessments for dams based on statistical analysis of recorded failures.

3.4 Observational approach

A modern observational approach to landslide management includes the setting up of monitoring stations, which may include rainfall pluviometers, inclinometers, piezometers and extensometers. Site-specific monitoring enables a more accurate understanding of performance and provides near real-time data during high-rainfall events. Observation and monitoring also facilitate the understanding of widespread landsliding (multiple occurrences of instability) after a triggering event such as heavy rainfall. Continuous or near real-time monitoring of rainfall, pore water pressure and landslide displacement has been carried out at more than 30 sites in the Wollongong study area. The data can be accessed through the internet in real time (Flentje *et al*., 2012). From the analysis of these data, the frequency of displacements exceeding certain magnitudes can be assessed, as can the frequency of pore pressures exceeding certain magnitudes. Such information can be valuable in decision-making about slow-moving landslides. Moreover, long-term data from landslide monitoring (periodic as well as continuous) can enable researchers to update previous assessments of landslide hazard and risk.

4. Landslide research in the Wollongong region, Australia, 1993–2016

4.1 Geological setting and landslide impacts in the region

The Illawarra escarpment comprises a Permian–Triassic-age geological sequence of essentially flat-lying interlayered sandstone, mudstone and coal of the Illawarra Coal Measures, overlain by interbedded sandstones and mudstones/claystones of the Narrabeen Group. Spectacular cliffs of Hawkesbury Sandstone (of Middle Triassic age) cap the escarpment, and there is dense vegetation over most of the escarpment below these cliffs. Most of the middle and lower escarpment slopes are covered by a colluvium mantle of various depths of up to ~20 m. Urbanisation of the Wollongong region has extended over many of these sloping areas of the escarpment. Consequently, the escarpment slopes and the temperate maritime climate with relatively high rainfall levels (up to 1800 mm annually) present a number of challenging hazards for the tenth-largest city in Australia. Figure 1 includes an oblique aerial photograph of the Illawarra escarpment in the northern end of the study area. The head scarp of a typical slide–flow-category landslide is shown in Figure 2.

Local and state government organisations and others have been associated with slope stability and landslide management issues for many decades. The efficient and safe operation of transportation routes has been one important focus of landslide management. The other equally important aspect is the safety and integrity of residential communities in the sloping areas of the region. The preservation of the environment and natural heritage in the Wollongong local government area has been reflected in continuing investigations and representations by diverse community groups and technical experts over many decades. The Illawarra Escarpment, an imposing and significant part of the whole region, was the focus of a significant commission of inquiry which completed a detailed report (Simpson, 1999). Issues related to landslide occurrence and management were also included in this report in submissions made by the authors of this paper and others.

The cumulative economic and environmental losses caused by landslides to local communities and regions are often significantly large, if not as dramatic as those associated with major earthquakes and floods. It has been estimated that, for the Greater Wollongong area of NSW, Australia, landsliding since 1950 has caused economic losses to infrastructure, housing and other assets of about US$225 million (Palamakumbure *et al*., 2015a). This approximate estimate is based on amounts spent on investigations and remedial works for a limited number of sites and does not include social and environmental costs or business losses. The real economic losses are expected to be much higher.

Fortunately, loss of life due to landslides has been relatively low in the urban areas of NSW, and indeed for the whole of Australia. Only five lives have been lost since 1900 in the Wollongong study region and 138 in the whole of Australia. The most dramatic examples in NSW are two deaths due to the Coledale embankment collapse and the landslide of 30 April 1988 in the Wollongong region and 18 deaths due to the 1997 Thredbo landslide in the Snowy Mountains region of NSW (Hand, 2000). In August 1998, the Wollongong region, experienced a major rainfall event with 750 mm of rain falling within a 4-d period. This resulted in the occurrence of 142 landslides, with only one life lost due to flooding. Half of these 142 events were first-time failures, while the others were reactivations of known landslides. An emergency response team was formed by the NSW Police and Emergency Services during the event and it included the Wollongong City Council (WCC) and the UOW LRT. The team produced a technical report covering the risk assessments of the mapped landslide events. The procedures developed in this post-landslide inspection, assessment and reporting process led to a proposed local government landslide action plan.

4.2 Introduction to the regional study

The UOW LRT has been involved in this long-term research project since 1993. As stated earlier, the three major aspects of continuing research are (*a*) assessment of landslide susceptibility and hazard, (*b*) landslide-triggering rainfall thresholds and (*c*) the monitoring of rainfall, pore water pressures and subsurface displacements (periodic as well as continuous). Owing to space limitations, details of only the first aspect are given in this section.

The area chosen within the Wollongong Region for modelling landslide susceptibility (susceptibility model area) extends to

550 km^2 and contains 480 slide-category landslides (the landslide inventory (LI) has 1849 landslides in total).

The data sets used for this study have been described in detail elsewhere (e.g. Flentje, 2009) and include geology (mapped geological formations, 21 variables), vegetation (mapped vegetation categories, 15 variables), slope inclination (continuous floating point distribution), slope aspect (continuous floating point distribution), terrain units (buffered water courses, spur lines and other intermediate slopes), curvature (continuous floating point distribution), profile curvature (continuous floating point distribution), plan curvature (continuous floating point distribution), flow accumulation (continuous integer) and wetness index (continuous floating point distribution).

4.3 Role and influence of UOW research

Research since 1993 has underscored the importance of an accurate and detailed LI for the development of strategies concerning landslide management. The authors' inventory has led to increasingly accurate landslide susceptibility maps. It has facilitated the selection and prioritisation of sites for detailed subsurface monitoring, in particular those affecting infrastructure such as roads and rail lines. Reliable susceptibility/hazard maps and successful monitoring strategies have led to a more productive collaboration with industry partners representing WCC, Road and Maritime Services (RMS) and Sydney Trains (formerly RailCorp).

4.4 LI and susceptibility modelling

The LI for this study has been developed over a 15-year period and comprises a relational Microsoft Access and Environment Systems Research Institute (ESRI) ArcGIS geodatabase with 75 available fields of information for each landslide site. It contains information on a total of 1849 landslides (falls, flows and slides), including 480 slides within the model area. Among the 480 landslides, approximate landslide volume has been estimated for 378 of these sites. The average volume is 21 800 m^3 and the maximum is 720 000 m^3.

The specific knowledge-based approach used for analysis and synthesis of the data sets for this study is the data mining (DM) process or model. The DM learning process is facilitated by the software See 5, which is a fully developed application of C4.5 (Quinlan, 1993). The DM learning process helps extract patterns from the databases related to the study area. Known landslide areas are used for one-half of the model training, the other half comprising randomly selected points from within the model area but outside the known landslide boundaries. Several rules are generated during the process of modelling. Rules which indicate potential landsliding are assigned positive confidence values, and those which indicate potential stability (no landsliding) are assigned negative confidence values. The rule set is then reapplied within the GIS software by using the Esri Model Builder extension to produce the susceptibility grid. The complete process of susceptibility and hazard zoning is described by Flentje (2009) and in chapter 11 of Chowdhury *et al*. (2010). The landslide susceptibility modelling process has been significantly improved and automated with the development of an ArcGIS toolbar add-in (Palamakumbure *et al*., 2015a). The modelling work has been extended to cover the Sydney Basin region, an area of 36 000 km^2 for the slide category and separately for flow-category landsliding (Palamakumbure, 2015; Palamakumbure *et al*., 2015b).

4.5 Susceptibility and hazard outcomes

4.5.1 Classification of zones

The susceptibility classification that has been developed for Wollongong relates to slide-category landslides only. The susceptibility modelling of slides (Figure 5) has classified 8·5% of the study area (approximately 64·7 km^2) as high susceptibility. This area contains 76% of the known landslides with a density of 38·8%. The moderate-susceptibility class covers nearly 3% of the study area (22·8 km^2) and contains 20% of the landslide population with a slide density of 29%. The area of the low-susceptibility class is 95·1 km^2 (12·5% of the study area) and contains 3% of the landslide population with a density of 1%. Almost 76% of the study area, approximately 578·5 km^2, has been classified as very low susceptibility, containing 1% of the landslide population with a density of 0·06%. Additional information is summarised in Table 1. Frequency as used here is the ratio between the number of occurrences and the reported time period. The average value reported is the average per zone for all the landslides in that zone.

4.5.2 Hazard assessment: additional information

The slide-category susceptibility maps described earlier have been enhanced with additional detail regarding landslide volume, frequency and potential travel distance. This information appears as unique landslide site labels for each site and with text boxes appearing on the map sheet frame outlining the distributions and averages of these values for each of the individual hazard zones. With these additional details, the maps can be regarded as slide-category hazard maps. On these maps, the susceptibility and hazard zones have the same boundaries.

5. Progress in sustainable landslide management related to UOW landslide research

5.1 Introduction to this section

Most of the research carried out by the UOW LRT has influenced the landslide risk management practice regionally and nationally, and both directly and indirectly. The direct influence has been through the development of the LI and the associated landslide susceptibility zonation maps. The indirect influence has been through the continual exchange of information and data between the industry partners on the one hand and the university researchers on the other. One of the authors of this paper (Flentje) was a co-author of the Australian Geomechanics Society's guidelines for landslide risk management (AGS, 2007). In turn, those guidelines have been widely accepted by the national and international geotechnical communities (Fell *et al*., 2008).

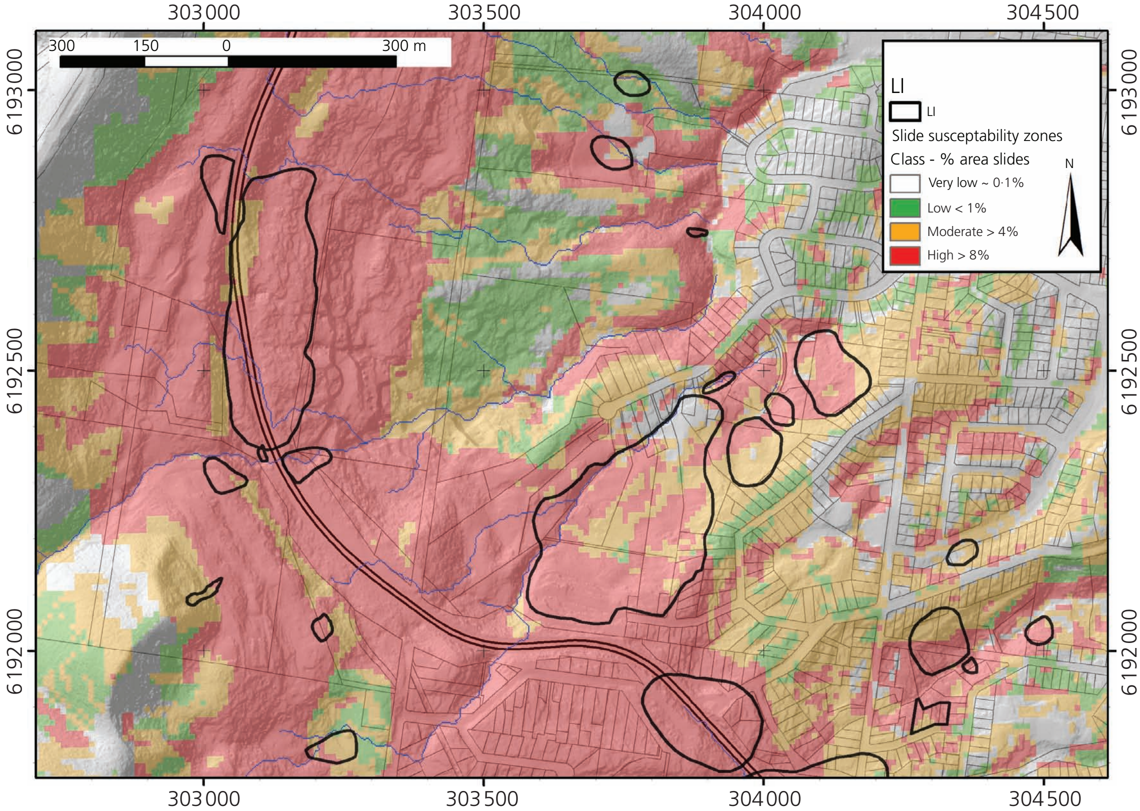

Figure 5. Segment of LI and susceptibility zoning map, showing Mount Ousley Road and residential parcel boundaries, Wollongong local government area, NSW, Australia. The image is centred at 34·4° south and 150·9° east

5.2 Specific benefits of research

An effective and efficient system has evolved at the local government level for the planning of residential development or redevelopment in the region based on known landslide locations, landslide susceptibility and hazard zonings with attendant local government policy. The system provides pathways for improved decision-making on applications for development of individual dwellings or multiple-dwelling structures and/or mixed developments adjacent to transport corridors.

Several recent infrastructure projects in the Wollongong region have involved substantial landslide mitigation works (see Sections 5.3 and 5.4). As a consequence of these projects and other collaborations between UOW LRT and different industry partners, there is now greater community awareness about the management of rainfall-triggered landsliding.

Local authorities are now using alert and warning procedures with greater confidence than before because of the network of

Hazard description	Landslide annual average frequency		Maximum landslide volume: m^3	Average landslide volume: m^3
	1880–2006	1950–2006		
Very low	0·0098	0·0165	36 300	3500
Low	0·0102	0·0172	4700	1450
Moderate	0·0125	0·0221	45 000	5700
High	0·0144	0·0247	720 000	28 700

Table 1. Zones of landslide frequency and volume based on the LI

continuous monitoring stations (see Section 3.4). Confidence has increased among the stakeholders in the use of slope monitoring and observational approach at significant sites. Such monitoring facilitates the planning and installation of preventive or remedial actions for landslide hazard reduction. This has also resulted in enhanced collaboration between researchers, industry partners, government agencies, professional engineering institutions and environmental groups.

5.3 Landslide management practice and projects in the region

Local geological and geotechnical details (soil structure, permeability, saturation, pore water pressure, existing slip surfaces and the presence of suctions in unsaturated soils) are often very important for devising and implementing practical solutions and for a more accurate understanding of failure mechanisms.

The most widely used remedial measures in the region are surface drainage, deep longitudinal drains, lateral subsurface drainage systems, drainage wells and retaining systems, including walls, rock bolts, gabions and wire barriers for containing rockfalls.

Besides engineering and other technical factors, remediating slopes and landslides along transportation routes requires careful consideration of safety, control of access and available budgets, which can influence both the choice of engineering solutions and the timing of implementation.

As an example of impact of budgets, even isolated landslides on minor urban roads may require investment of millions of dollars. Referring to minor roads in the Wollongong region of NSW, Tobin (2012) estimated \$A2·7 million for a proactive response to remediate three rockfall hazards and four landslide hazards on Mount Keira Road. These amounts are in accord with estimates, based on research, of historical expenditure since 1950 on landslide remediation and management, as referenced earlier.

5.4 Landslide projects completed in the region since 1993

Numerous projects have been investigated and successfully managed since 1993. These projects, carried out in a well-structured and scheduled sequence, are evidence of the resilience and sustainability of the landslide management strategy. These include remedial works along (*a*) Mount Keira Road; (*b*) Harry Graham Drive; (*c*) Bulli Pass; (*d*) Lawrence Hargrave Drive, including the Sea Cliff Bridge; (*e*) Mount Ousley Road; and (*f*) rockfall from Mount Keira summit. The last two are briefly discussed in the following sections.

5.4.1 Site 141: Mount Ousley Road landslide

This is one of three main landslide sites along the Mount Ousley Road (part of the main M1 highway linking Sydney and Wollongong). This motorway carries approximately 50 000 vehicle movements per day. The slip surface is located up to 20 m below ground level. High pore water pressure was found to be the cause of landsliding; thus, the site was stabilised in the early 1970s with a subsurface drainage system incorporating 20 vertical relief wells, each 30 m deep, with groundwater pumps installed in nine. Due to the site geomorphology and the deep artesian aquifer, pore water pressure reduction cannot be achieved by gravity alone. The solution has worked acceptably for decades, and with periodic monitoring and maintenance, the traffic on the highway has not been seriously disrupted. Although subsurface displacements have occurred, the magnitude has been kept low enough (millimetres) to prevent, contain or restrict any damage to the road surface.

In recent years, detailed and continuous monitoring has shown the frequency of significant pore pressure rises associated with these small-magnitude movements to be higher than acceptable (Flentje *et al*., 2010). The performance of the site as a whole, and in particular of the pumping systems, was put under the spotlight. This has led to a decision by the RMS to invest US\$1·12 million in 2015 on a significant upgrade of the remedial systems, including new pumps and a real-time management system, in consultation with the NSW Public Works and the LRT (UOW).

5.4.2 Site 670: rockfall at Mount Keira Summit Park

This rockfall at Mount Keira developed in a progressive manner with occurrence of minor, almost undetectable, lateral movements. This gradually led to the opening of joints and cracks and to dislodging of pieces of rock from the jointed rock mass and then the occurrence of a full-fledged rockfall (midday, 25 April 2007). Because of the location and limited travel distance, the rockfall has not had an adverse impact on residential areas. As soon as early signs of displacement and cracking of the cliffs were noted, the area was cordoned off and signs were placed to warn the visitors. The rockfall trajectories have cleared a path through the steep forested slopes, and the debris has been deposited within the densely wooded terrace area below. Rockfalls at this site continue to occur intermittently, with imminent failure of some very large semi-detached blocks expected.

Research and modelling has been carried out to interpret the two-dimensional and three-dimensional trajectories and distribution of the rockfall debris. The investigations at this site and several other rockfall sites along the Illawarra Escarpment are the basis of rockfall susceptibility and hazard management in this region (Flentje *et al*., 2015).

5.5 Checklist of approaches to sustainable urban landslide management

Table 2 provides a basic checklist of the methods to be used for sustainable landslide management in an urbanised region and the associated assumptions concerning community impact and consultation with stakeholders. This is proposed from professional experiences of the authors as well as an understanding of national and international practice.

Purpose	Best approach to use
Regional planning	LI, susceptibility and hazard maps/assessments
Preliminary assessment for remediation	Qualitative hazard and risk assessment
Prioritisation of sites for remediation	Detailed risk assessment, QRA
Design of slopes/remedial actions	Stability analyses and probabilistic analyses, engineering design and details

Landslide management is dependent on the availability of adequate resources, allocation of budgets and development of suitable timelines. Due consideration of community needs and of environmental and social impacts involves ongoing processes of consultation and discussion among all stakeholders. Active involvement of stakeholders is most helpful in securing budgets in a timely manner. Careful consideration must be given to scheduling of remedial works so that minimum disruption is caused to public and other stakeholders

Table 2. Sustainable management of landslides – basic checklist for urbanised areas/regions

6. Urban landslide management: Hong Kong

6.1 Sloping terrain and the adverse impacts of landsliding

The natural sloping terrain of Hong Kong has been modified to create platforms for buildings and benches for roads. Thus, steeply cut slopes have been created in or close to many urban areas. Such processes often expose joints and other discontinuities which are orientated unfavourably from a geotechnical stability perspective. Sometimes the excavated soil is deposited in unacceptable locations and poorly compacted, which can be hazardous. As the ground is disturbed by excavation and construction processes, the equilibrium of natural drainage systems is altered. These important factors (steepened slope inclinations, daylighting joints, disturbed drainage, inadequately compacted fills) contribute to a significant increase in the hazard of landsliding in both the short and long terms. In a tropical city with a high population density and high rainfall such as Hong Kong, with intense physical development, the consequences of landsliding are very high. Consequently, there has long been an awareness of the need and urgency of landslide mitigation, as well as long-term risk management.

A comprehensive assessment of the adverse economic impact of landslides in Hong Kong is not available. However, millions of dollars have been spent in upgrading man-made slopes, and some details of these costs are given in the following paragraphs. Human safety concerns due to landslides have always been high in Hong Kong because of the occurrence of significant fatalities from time to time. It has been estimated (Choi and Cheung, 2013) that 470 lives were lost in Hong Kong due to landslides over a period of 65 years (1947–2012).

6.2 Multistage approach to slope upgrading

Before the gradual evolution of a risk-based approach to landslide assessment and management in Hong Kong, a conventional engineering approach was followed for the upgrading of man-made slopes. Several geotechnical manuals, technical reports and guidance notes have been developed, such as a slope manual (Geo, 2011) and a manual on engineering geological practice (Geo, 2007a). Besides these, several publications deal with different engineering methods of slope upgrading, such as retaining wall design, bioengineering and the use of soil nails. A catalogue of 60 000 man-made slopes was registered in the early 1970s, according to Choi and Cheung (2013). A landslide preventive measure (LPM) programme for man-made slopes involving retrofitting of substandard slopes was envisaged in 1977. A total of 620 slopes affecting occupied buildings had been upgraded by 1994 at a cost of approximately US$155 million. The design and construction involved four stages: stage 1 – preliminary study; stage 2 – detailed study; stage 3 – design of slope to required safety standard; and stage 4 – construction of slope works.

6.3 Evolution of risk-based approach

Following a fatal landslide on 23 July 1994 and recommendations of an expert panel, a slope safety review was ordered by the government towards the end of 1994. In April 1995, a 5-year accelerated LPM programme was launched in April 1995. This included upgrading of 800 substandard government-owned man-made slopes, as well as safety screening of 1500 private man-made slopes.

A risk-based priority ranking system was followed which used the results of QRA. This involved both the likelihood of the landslide and the consequences of the slope failure. A total score was based on the product of instability score and consequence score. From 1995 to 2000, a total of 794 slopes were upgraded under the LPM at a cost of HK$2930 million. After these 5 years, 250 slopes were upgraded each year, five or six times the average before 1995. An assessment of the reliability of the accelerated LPM process showed that the overall landslide risk was reduced to 50% of the level in 1977.

Beginning in 1977, a 10-year extended LPM strategy was launched by the government with the aim of reducing landslide risk to 25% of the 1977 level. This comprised annual upgrading of 250 government slopes and safety screening of 300 private man-made slopes. Total upgrading from 1977 to 2010 was to 4500 man-made government slopes at a cost of HK$14 billion. The average annual expenditure increased from HK$60 million (pre-1995) to HK$900 million (1995–2000) and to HK$950 million (2000–2010).

The government has also implemented a landslide prevention and mitigation programme since 2010 with the strategy of containing the remaining landslide risk (from about 15 000 man-made slopes) through improvement of man-made slopes and systematic mitigation of risk associated with natural terrain landslides.

The conclusion of the overview by Choi and Cheung (2013) is that the upgrading of slopes has contributed significantly to hazard reduction and sustainable landslide risk management.

6.4 Engineering methods used in upgrading of man-made slopes in Hong Kong

A variety of well-known slope upgrading methods have been used in Hong Kong. These include reducing the slope inclination where feasible, using retaining walls and buttresses, using soil nails (for cut slopes and also some fill slopes), drainage and a combination of these. Inadequately compacted fill slopes are excavated and rebuilt to a high standard of compaction.

The residual soils of Hong Kong are unsaturated with high negative pore pressures prevailing, in particular, during dry periods. During high rainfall, negative pore pressures are dissipated as a wetting front advances downwards. Positive pore pressures may develop close to the surface; therefore, surface drainage can be effective in controlling shallow slope failures under such conditions.

Bioengineering solutions, such as planting particular species of trees, have also been applied to upgrade slope stability (Geo, 2007b). In some instances, vegetation cover has been primarily provided to improve the appearance of upgraded slopes and to prevent erosion, rather than to strengthen against instability.

Upgrading of rock slopes includes scaling of loose surface materials, buttresses, rock bolts, mesh netting and drainage. An accurate evaluation of joint systems with their direction and spacing is required before designing remedial measures in rock slopes.

6.5 Influence of geotechnical research on risk management practice

Considerable research effort has been made in Hong Kong by the geotechnical control office and the local universities. Early research was carried out by a number of researchers and engineers, such as those on behaviours of unsaturated soils (Lumb, 1975) and mechanisms of slope failures triggered by high rainfall (Brand, 1982). Since then, there has been research over many topics and there is a vast body of research literature embracing theory, analysis and practice. Only a few are cited in this paper (Cheng, 2011; Hungr *et al*., 2007; Wong, 2005).

The influence of research on slope engineering practice has been significant in enabling the use of more efficient methods of analysis and design. The research community has benefitted from the wealth of data available from investigation and testing as well as the data from performance of slopes.

7. Summary and conclusions

7.1 Summary of Wollongong case study

Sustainable landslide management practice in Wollongong has evolved over more than two decades. During the same period, the authors have developed a comprehensive, field-based programme of research in this region. Owing to space limitations, only the key details of landslide susceptibility and hazard assessment have been provided in this paper. Aspects of this research concerned with landslide susceptibility zoning are now being extended to the whole of NSW and beyond. There are several other aspects to this Wollongong research, including detailed observational approaches, which have not been covered in detail due to space limitations. The other areas include continuous monitoring, development of warning and alert systems and methods of reliability analysis. More information about these topics is provided in the references included at the end of this paper. These have been cited at appropriate places in the text.

Research studies and productive collaboration in Wollongong, Sydney and the surrounding areas with practising engineers and decision makers have had the most influence on the development of sustainable landslide management practice. Many projects have been carried out successfully by the relevant authorities with due regard to confidence among residents and other stakeholders about the protection of the environment and human safety. A collaborative, result-oriented process has facilitated the availability of financial support for research.

In the urban areas, many landslides occur in the colluvium covering the underlying bedrock. Water tables in the underlying bedrock and colluvium rise during heavy rainfall, leading to high pore water pressures on potential slip surfaces. There are, of course, some deep-seated landslides in which landslide movement occurs along joints and other discontinuities in rock. A rapid rise in pore water pressures associated with rainfall infiltration and seepage is an important factor in the stability of slopes, whether the potential slip surfaces are shallow or relatively deep.

The greatest care is needed with regard to slow-moving landslide sites, in particular those which impact the safe operation of busy transport routes (road and rail). The sites may appear to be stable over long intervals, even during heavy rainfall, but surface appearance is often deceptive. Both surface and subsurface monitoring are important, and pore pressure and displacement data must be analysed, preferably on a continuous basis.

7.2 Summary review concerning Hong Kong case study

Hong Kong has many man-made slopes of significant height and with steep inclinations in urban areas; thus, both the hazard and potential consequences can be high. Based on an understanding of local geological and geotechnical details, a multipronged preventive or remedial strategy is often adopted. Retaining and strengthening approaches are far more common in Hong Kong than in Wollongong. The role of subsurface drainage and in particular deep drainage is less prominent compared to that in Wollongong for the following reason.

Hong Kong has residual soils in which the water table is often located at considerable depth, and there are considerable negative pore water pressures. During heavy rainfall, the rise in the water table in most situations is not significant. Infiltration of rainfall eliminates the negative pore pressures close to the slope surface, and positive pore water pressures may also develop with perched water tables. At deeper levels, negative pore pressures persist; therefore, pore pressure is not a factor in assessing potential for slip along deep slip surfaces. Understandably, therefore, deep drainage systems are rarely mentioned in the literature as part of landslide management systems. However, good engineering practice dictates provision of surface drainage in slopes and drainage hole outlets in retaining structures.

7.3 Conclusions on research and practice

Sustainable practices for urban landslide management have been developed in both the Wollongong region of NSW, Australia, and Hong Kong. Research on geotechnical aspects has been carried out consistently over recent decades. In Wollongong, university-based research and interaction between researchers and industry partners has contributed to the development of field-based approaches for susceptibility and hazard zoning as well as effective observational approaches. In turn, sustainable and resilient approaches to landslide management have evolved and progressed.

In Hong Kong, research has been carried out directly by the government and also by universities and the industry. Interestingly, as in Wollongong, sustainable landslide management practice in Hong Kong over the last three decades has also developed side by side with comprehensive research studies. However, significant differences between landslide occurrence and management in the Wollongong urban area and Hong Kong must be noted. Geological and geotechnical settings are very different between Wollongong and Hong Kong. The hazard–consequence approach has been considered useful, although there seems to be less mention of susceptibility and hazard zoning in the literature on landslide management in Hong Kong. The focus has been on management of individual man-made slopes, which can present significant challenges in comparison to natural slopes. There are also differences in the preventive and remedial solutions. Nevertheless, risk assessment processes have been adopted and developed in both Wollongong and Hong Kong, although the scope and details may be different in some respects.

7.4 Future challenges for research concerning sustainability

In this paper, continual improvement of landslide management has been described and the link to sustainability and resilience is implied. Direct or specific studies concerning sustainability and resilience have rarely been reported. This is because slopes and landslides are only one aspect of urban development and infrastructure systems which must be planned and implemented with particular attention to sustainability and resilience. The main challenges posed include life-cycle analyses and the assessment of residual risk after implementation of risk-reduction measures. The life cycle of the remedial works must be assessed and managed to be consistent with the life cycle of the infrastructure itself. Based on the availability of long-term data, research studies could be justified for major landslides considered in isolation. For smaller landslides within an urban region or along a transport corridor, sustainability research should be for the whole facility with due consideration given to the contribution of landslide remediation and to the role of particular management strategies. In research studies for resilience and sustainability, it would also be necessary to include the role of public against private funding of projects and the costs of ongoing maintenance.

REFERENCES

AGS (Australian Geomechanics Society) (2007) Commentary on practice note guidelines for landslide risk management. *Australian Geomechanics* **42(1)**: 115–157.

Anderson M and Holcombe E (2013) *Community-based Landslide Risk Reduction – Managing Disasters in Small Steps*. World Bank, Washington, DC, USA.

Brand EW (1982) Moderator's report on slope stability with special reference to residual soils. *Proceedings of the 7th Southeast Asia, Geotechnical Conference, Hong Kong*, vol. 2, pp. 27–57.

Cheng PFK (2011) *Assessment of Landslide Risk Posed by Man-made Slopes as of 2010*. Geotechnical Engineering Office, Hong Kong Special Administrative Region Government, Hong Kong, China, Special Project Report Number SPR1/2011.

Chigira M, Wu X, Inokuchi T and Wang G (2010) Landslides induced by the 2008 Wenchuan earthquake, Sichuan, China. *Geomorphology* **118(3–4)**: 225–238.

Choi KY and Cheung RWM (2013) Landslide disaster prevention and mitigation through works in Hong Kong. *Journal of Rock Mechanics and Geotechnical Engineering* **5(5)**: 354–365.

Chowdhury R, Flentje P and Bhattacharya G (2010) *Geotechnical Slope Analysis*. CRC Press, Boca Raton, FL, USA.

Chowdhury R, Flentje P and Bhattacharya G (2012) Geotechnics in the 21st century: uncertainties and other challenges, with particular references to landslide hazard and risk assessment. *Proceedings of International Symposium on Engineering under Uncertainty, Safety Assessment and Management (ISEUSAM – 2012), Shibpur, India*, pp. 27–43 (CD-ROM).

Fell R, Corominas J, Bonnard C *et al.* (2008) Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning. *Engineering Geology* **102(3–4)**: 99–111, http://dx.doi.org/10.1016/j.enggeo.2008.03.014.

Flentje P (2009) *Landslide Inventory Development and Landslide Susceptibility Zoning in the Wollongong City Council Local Government Area*. University of Wollongong, Wollongong, Australia.

Flentje P, Chowdhury R, Miner AS and Mazengarb C (2010) Periodic and continuous landslide monitoring to assess landslide frequency – selected Australian examples. In *Geologically Active: Proceedings of the 11th IAEG Congress of the International Association of Engineering Geology and the Environment, Auckland, New Zealand* (Williams AL, Pinches GM, Chin CY, McMorran TJ and Massey CI (eds)). CRC Press, Boca Raton, FL, USA, pp. 1–11 (CD-ROM).

Flentje P, Chowdhury R, Miner AS and Mazengarb C (2012) Quantitative assessment of landslide frequency versus magnitude of displacement. *Proceedings of the 11th International and 2nd North American Symposium on Landslides, Banff, Alberta, Canada*, pp. 1–7.

Flentje P, Palamakumbure D and Thompson J (2015) Assessing rockfall along the Illawarra Escarpment. In *Engineering Geology for Society and Territory* (Lollino G, Giordan D, Crosta GB *et al.* (eds)). Springer, Cham, Switzerland, vol. 2, pp. 2031–2036. See http://link.springer.com/chapter/10.1007/978-3-319-09057-3_361 (accessed 08/11/2016).

Geer (Geotechnical Extreme Events Reconnaissance) (2015) *Geotechnical Field Reconnaissance: Gorkha (Nepal) Earthquake of April 25, 2015 and Related Shaking Sequence*. Geer Association, Berkeley, CA, USA, Report No. GEER-040, version 1.1.

Geo (Geotechnical Engineering Office) (2007a) *Engineering Geological Practice in Hong Kong*. Geotechnical Engineering Office, Hong Kong, China, GEO Publication 1/2007.

Geo (2007b) *Technical Guidance on Landscape Treatment and Bio-engineering for Man-made Slopes and Retaining Walls*. Geotechnical Engineering Office, Hong Kong, China, Geo TGN No. 20.

Geo (2011) *Geotechnical Manual for Slopes*, 2nd edn. Geotechnical Engineering Office, Hong Kong, China.

Gibson AD and Chowdhury R (2009) Planning and geohazards.. In *Engineering Geology for Tomorrow's Cities* (Cullshaw MG, Reeves HJ, Jefferson I and Spink TW (eds)). Geological Society, London, UK, Engineering Geology Special Publication, vol. 22, pp. 113–123.

Hand D (2000) *Coroner's Report of the Inquiry into the Deaths Resulting from the Thredbo Landslide*. New South Wales Department of Justice, State Coroner, Sydney, Australia.

Hungr O, Morgenstern NR and Wong HN (2007) Review of benchmarking exercise on landslide debris runout and mobility modeling. In *Proceedings of the 2007 International Forum on Landslide Disaster Management, Hong Kong* (Ho K (ed.)). Hong Kong Institution of Engineers, Hong Kong, China, pp. 755–812.

Kumar N and Sindhupalchok (2016) Why Nepal is still in rubble a year after a devastating quake. *Time*, 24 April.

Lumb P (1975) Slope failures in Hong Kong. *Quarterly Journal of Engineering Geology and Hydrogeology* **8**: 31–65.

Palamakumbure D (2015) *GIS-based Landslide Inventory and Landslide Susceptibility Modelling across the Sydney Basin*. PhD thesis, Faculty of Engineering, University of Wollongong, Wollongong, Australia.

Palamakumbure D, Stirling D, Flentje P and Chowdhury R (2015a) ArcGIS V.10 landslide susceptibility data mining add-in tool integrating data mining and GIS techniques to model landslide susceptibility. In *Engineering Geology for Society and Territory* (Lollino G, Giordan D, Crosta GB *et al.* (eds)). Springer, Cham, Switzerland, vol. 2, pp. 1191–1194. See http://link.springer.com/chapter/10.1007/978-3-319-09057-3_208 (accessed 08/11/2016).

Palamakumbure D, Flentje P and Stirling D (2015b) Flow category landslide susceptibility modelling of the Sydney Basin. *Changing the Face of the Earth: Geomechanics and Human Influence – Proceedings of the 12th Australia New Zealand Conference on Geomechanics, Wellington, New Zealand*, pp. 1–6.

Petley D (2012) Global patterns of loss of life from landslides. *Geology* **40(10)**: 927–930.

Petley D, Dunning S, Rosser N and Kausar AB (2006) Incipient landslides in the Jehlum valley, Pakistan following the 8th October 2005 earthquake. In *Disaster Mitigation of Debris Flows, Slope Failures and Landslides* (Marui H (ed.)). University Academy Press, Tokyo, Japan, Frontiers of Science Series 47, pp. 47–55.

Quinlan R (1993) *C4.5: Programs for Machine Learning*. Morgan, San Mateo, CA, USA.

Simpson W (1999) *The Long Term Planning and Management of the Illawarra Escarpment, Wollongong Local Government Area: Report to the Honourable Dr Andrew Refshauge…/Commissioner William Simpson, Chairman, Commissioners of Inquiry for Environment & Planning*. Office of the Commissioners of Inquiry for Environment and Planning, Sydney, NSW, Australia.

Tobin PR (2012) Managing slope instability hazards affecting local roads within the City of Wollongong. *Australian Geomechanics* **47(1)**: 53–58.

UNISDR (UN Office for Disaster Risk Reduction) (2012) *How to Make Cities More Resilient: a Handbook for Local Government Leaders*. UNISDR, Geneva, Switzerland.

WEF (World Economic Forum) (2015) *Building Resilience Nepal through Public–Private Partnerships*. WEF, Cologny, Switzerland.

Wong HN (2005) Landslide risk assessment for individual facilities. In *Proceedings of the International Conference on Landslide Risk Management, Vancouver, Canada* (Hungr O, Fell R, Couture R and Eberhardt E (eds)). Taylor & Francis, London, UK, pp. 237–296.

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